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Comparing Layer Types for the Use of MEPDG for FDR Design

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ABSTRACT

While Full Depth Reclamation (FDR) has many potential cost and environmental benefits, especially over the lifetime of the pavement, it is necessary to be able to ensure that the recycled pavement will perform adequately. One way in which this can be accomplished is understanding how to best complete the structural design of FDR pavements. Because FDR is a combination of several different layers of material pulverized, mixed, stabilized and re-compacted, it does not fit neatly into any of these predetermined types of materials considered by the Mechanistic Empirical Design Guide (MEPDG). Current practice is to treat FDR as an unbound granular base layer, but this does not account for the added stability of the selected stabilization technique. However, previous research has shown that FDR may be more accurately characterized as a less-aged asphalt concrete. Until a new layer type is developed that considers the unique properties of these recycled, stabilized base courses, it is essential to understand how to use existing structural design tools to model FDR in a way that best captures its structural benefits. In this research, three different FDR mixtures, two of which were made from Arkansas highway materials, were designed and tested to obtain all necessary material properties required as inputs for the MEPDG to consider this material as both asphalt concrete (AC) and unbound granular material (UGM). Using traffic information from the two Arkansas highways and Arkansas climate data, two different MEPDG models were created for each mixture, one characterizing the FDR layer as an asphalt concrete and the other as an unbound granular material. A stronger correlation was found to exist between temperature and modulus, rather than stress state and modulus. All distress predictions by the MEPDG were higher for the FDR as UGM except AC rutting for one mixture and bottom-up fatigue cracking. Overall, considering FDR as AC seemed to more accurately account for the structural benefits of FDR.

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INTRODUCTION

As America's infrastructure ages and is faced with an increasing population and heavier traffic demands, the condition of the country's roadways are deteriorating. Unfortunately, the funds available are insufficient to return these pavements to the desired level of performance (ASCE, 2013). Therefore, there is a need for an increased understanding of maintenance and rehabilitation techniques that can restore the long-term condition of a pavement in a cost-effective and environmentally friendly manner. One such technique that holds promise of providing this type of solution is Full Depth Reclamation (FDR).

Full Depth Reclamation

FDR is a pavement rehabilitation technique in which all of the asphalt pavement section, as well as a predetermined amount of underlying base material, are treated, pulverized, mixed and compacted to produce a thicker, stabilized base course (ARRA, 2001). FDR is typically performed to a depth of 4 to 12 inches. There are several major advantages to this technique. It completely eliminates and corrects pavement distresses extending below the surface layer, unlike many other maintenance techniques, and can actually increase the structural capacity of the pavement (Stroup-Gardiner, 2012). Additionally, the use of in-situ material can result in about 30 to 50 percent cost savings and cut down on greenhouse gas emissions by about 50 percent as well. In-place recycling procedures, such as FDR, are also much quicker than a full reconstruction project would be (Bowers, 2015).

Unfortunately, there are some hindrances to the implementation of FDR as well. Because the entire pavement section is incorporated, a single layer of subgrade soil, base aggregate, and asphalt concrete materials is created. Asphalt concrete is typically used for the upper layers in a flexible pavement structure because it is a much stiffer material due to the stability added by the asphalt binder. Granular bases and subgrade soils make up the lower layers of a flexible pavement structure. While they are not bound with a stabilizing additive, once compacted to the desired density, these materials can provide adequate load transfer to prevent pavement failure. FDR falls somewhere in between these two types of materials because, while it is treated with some type of stabilizing additive, it is not quite as stiff as asphalt concrete, but not as weak as unstabilized material. This composite layer is much more difficult to characterize because distinctly different material properties are typically used for performance prediction and design of each of these types of materials. Therefore, there is uncertainty regarding which laboratory tests and procedures are most necessary and most appropriate for this new, recycled base layer created through the FDR process. An immediate problem with these questions is the issue of the structural design of these recycled and rehabilitated pavements.

Structural Design

The structural design of pavements involves determining the thickness of the layer or layers that make up the pavement structure. The method historically used for design in the United States is an empirical method developed by the American Association of State Highway and Transportation Officials (AASHTO). This design guide, known as the 1993 AASHTO Design Guide, was developed based upon a series of road tests conducted in the late 1950's in Ottawa, Illinois. For flexible pavements, several inputs are used to generate a single structural number that quantifies the necessary structural capacity of the pavement as a whole. Then, structural layer coefficients (SLC) specific to the materials used are used to determine the thickness required for each layer to achieve this structural number.

This guide has gone through several iterations since its initial publication, but there are significant limitations to this method of design based primarily on observed performance of a small scope of materials, climate conditions, construction practices, and traffic applications (Timm *et al*., 2014). One instance of these limitations is the lack of consideration of recycled base materials, like FDR. From literature, there is a large variation in SLC's used and accepted for FDR materials, ranging from 0.27 to 0.41. These values, along with the stabilizing additive used in that particular mixture are displayed in Table 1. This variance illustrates the difficulty of selecting one standardized SLC for a composite material such as FDR, and consequently, the difficulty of designing FDR in a way that adequately captures its structural contribution to a pavement. However, at this point, according to responses Stroup-Gardiner received from contractors and state agencies about preferred method of structural design for FDR, using an AASHTO structural coefficient is most frequently used (2011).

TABLE 1. FDR SLC's From Literature

Research	Stabilizing Additive	SLC
Butalia *et al*., 2011	Lime + Fly Ash	0.37
	Cement + Emulsion	0.27
	Cement	0.41
	Lime Kiln Dust + Emulsion	0.26
	Lime Kiln Dust + Fly Ash	0.36
Mallick *et al*., 2002	Emulsion	0.24
	Cement	0.28
	Emulsion + Lime	0.37
Marquis *et al.,* 2003	Foam + Cement	0.26
Thomas & May, 2007	Emulsion	0.25

Mechanistic Empirical Design Guide

The Mechanistic-Empirical Design Guide (MEPDG) was developed as an improvement from the previous 1993 AASHTO Design Guide. The MEPDG allows for more accurate performance prediction and material characterization by requiring specific material properties, climate data, and expanded traffic data as inputs. While this method of structural design has made considerable improvements from the 1993 AASHTO Design Guide, there is still much more work to be done.

Research has indicated that the MEPDG does not currently consider the unique properties of the composite layer created by FDR using asphalt stabilization (Thomas and May, 2007). May identified several limitations of the MEPDG regarding the design of new and innovative asphalt bound mixtures like FDR, including the need for more flexibility in data entry for low temperature cracking, allowance for entry of thinner wearing courses as may be used with FDR, and the use of different fatigue models for each asphalt concrete layer. The current practice is to treat asphalt stabilized FDR as an unbound granular base layer, specifically as in place recycled asphalt pavement (RAP), but this does not account for the strength added by stabilizing the reclaimed material. Additionally, the current default resilient modulus associated with this unbound characterization is far too low (May, 2008). The MEPDG software does provide the option of a stabilized base course, however, the stabilization methods are only those used in chemical or cement stabilization for FDR. Therefore, FDR materials stabilized using either asphalt emulsion or asphalt foam are not directly considered. Another study found that there is a significant impact on the performance predictions when treating FDR as either an unbound layer or as an asphalt concrete layer (You *et al.*, 2012). In terms of rutting and fatigue cracking, treating the FDR as an asphalt concrete layer yielded the best performance predictions. However, the question arises as to whether or not this is accurately predicting the performance of FDR. The asphalt concrete rutting equation and fatigue cracking model used by the MEPDG may not apply to FDR, but the unbound granular material models may underestimate the contribution of FDR. Until a new layer type is developed to fully consider the unique properties of asphalt stabilized FDR, it is necessary to understand the effects of characterizing the composite FDR layer with the existing layer types, either asphalt concrete or unbound granular materials, and how these material property inputs affect performance prediction.

LABORATORY PLAN

The effectiveness of the existing MEPDG material characterization was evaluated for the design of FDR pavements by comparing the effects of considering asphalt emulsion stabilized FDR as an asphalt concrete material or as an unbound granular material. FDR incorporates both of these types of materials by pulverizing and mixing the entire pavement structure and then stabilizing it with the selected additive, creating a composite material. Within the MEPDG, different material properties are used to characterize asphalt concrete than those used for unbound granular materials. Both sets of properties were obtained for three different FDR mixtures stabilized with asphalt emulsion. Two different MEPDG models were then created for each FDR mixture in order to evaluate the effects of characterizing asphalt emulsion stabilized FDR as an asphalt concrete material versus characterizing it as an unbound granular base.

Materials

Three different FDR mixtures were designed and tested in this research. The North Carolina Department of Transportation's (NCDOT) mix design procedure for asphalt emulsion stabilized FDR was followed in this research. This mix design was selected because it is one of the few public FDR asphalt emulsion mix designs available in the United states, has been historically followed at the University of Arkansas, and is consistent with procedures found in literature (Hill and Braham, 2016; Thomas and May, 2007). In order to accurately model an FDR mixture as would be seen in the field, RAP, base course aggregate, and subgrade soil were combined in the appropriate ratios based upon an assumed reclamation depth of 8-inches. The first mixture was created using 50% Recycle B RAP and 50% Arkansas Class 7 aggregate base course from Sharps Quarry in Springdale, Arkansas. The remaining mixtures were created from field materials taken from two state highways in Central Arkansas. Highway 5 consisted of 75% RAP and 25% subgrade material, while Highway 36 was comprised of 62.5% RAP and 37.5% subgrade. Information regarding the age of these highways or the maintenance history was not available; however, it is important to consider that both of these things could significantly affect material properties and performance of these materials when combined into the FDR mixtures. The targeted gradation for all of these mixtures was to be within the ideal range specified by the Asphalt Academy for asphalt emulsion stabilized mixtures (2009). Unfortunately, after processing the materials sampled from Highway 5 and Highway 36, they were found to fall slightly above this range. It was decided that this initial gradation should be kept rather than altering it to fit within the ideal range as this was believed to simulate the field gradation. Figure 1 displays the combined gradations for each mixture, along with this recommended minimum and maximum.

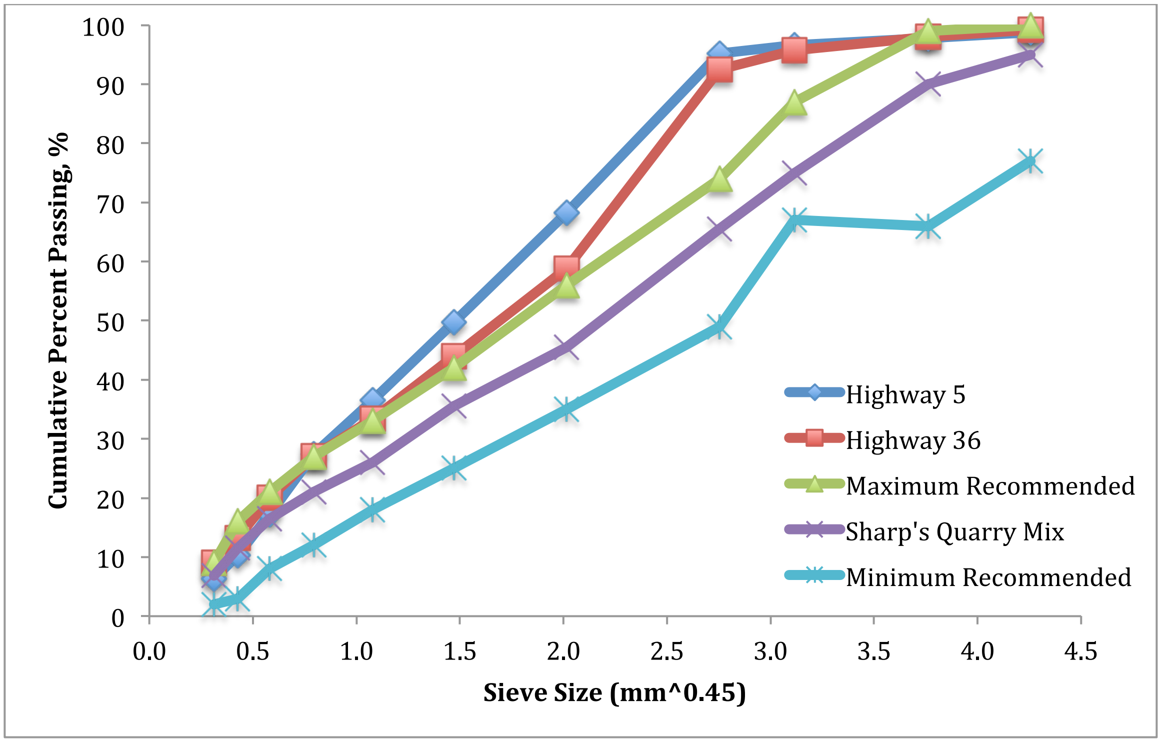


FIGURE 1. FDR Mixture Gradation

Prior to selecting the optimum asphalt emulsion content (OEC), several material properties were determined for the unbound mixtures. These properties, along with the test methods followed, are displayed in Table 2. According to the mix design, moisture-density relationships were determined using ASTM D1557 Method C, which gave the optimum moisture content (OMC) and the maximum dry density (MDD). The sand equivalency (SE) was also required by the mix design, along with the average annual rainfall, to determine what percentage of the OMC should be added when fabricating emulsion stabilized samples. The Atterberg Limits were determined as required inputs for the MEPDG and to allow for further material characterization and comparison of the mixtures. The Attergberg Limits, which were found according to ASTM D4318, include the Liquid Limit, Plastic Limit, and Plasticity Index and are used to classify soils and distinguish the boundaries of the consistency states of plastic soils. The Liquid Limit was found by spreading a portion of each unstabilized mixture in a brass cup, dividing it in two using a grooving tool, and then counting the number of drops of this cup it takes until the specimen flowed together. The liquid limit is then the moisture content at which this happens. The Plastic Limit is determined by taking the specimen at the water content of the liquid limit and rolling it into 1/8-inch diameter threads and continuing this process until those threads crumble. The Plastic Limit is the water content at the point of crumbling. Plasticity Index is then the difference between the Liquid Limit and the Plastic Limit.

TABLE 2. Unbound Mixture Properties

Property	Test Method	Sharp's Quarry Mix	Highway 5	Highway 36
Plasticity Index	ASTM D4318	Non-plastic	12	12
Liquid Limit		Non-plastic	28	27
OMC (%)	ASTM D1557	5.0	5.5	4.75
MDD (pcf)		121	132	130
% Passing No. 200 Sieve	ASTM D6913	6.85	6	9
Sand Equivalent	ASTM D2419	90	22	21

The Asphalt emulsion used was provided by Ergon, Inc. This is a cationic medium set emulsion, referred to as CIR-EE, made using a base binder of PG 64-22. The residue for this asphalt emulsion was obtained according to AASHTO PP72, and this emulsion was 63% asphalt binder. The asphalt emulsion was poured into an aluminum tray and placed in an oven at 140°F for six hours. At the end of that six hours, the remaining asphalt binder was weighed to determine the final emulsion residue. A Dynamic Shear Rheometer (DSR) was used to determine the rheological properties of the emulsion residue (AASHTO T315). The 25-mm parallel plate geometry on the DSR was used for this testing configuration, which is displayed in Figure 2.

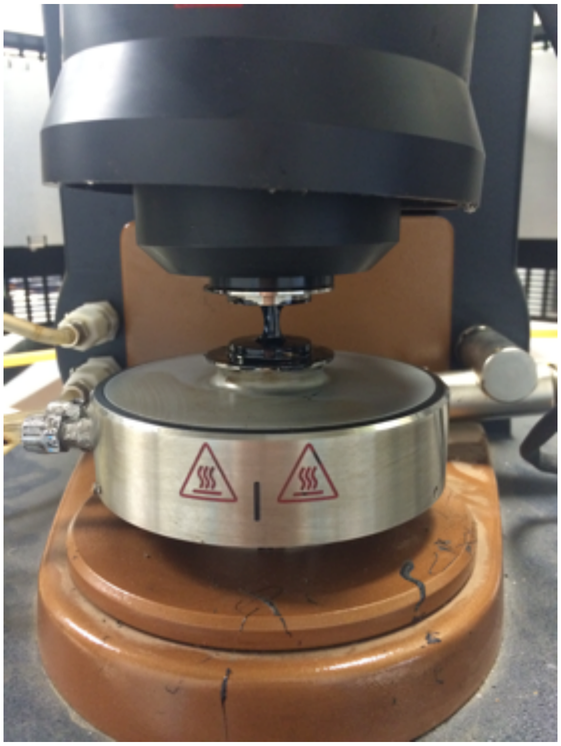


FIGURE 2. Determination of Rheological Properties of Asphalt Emulsion using DSR (Photo taken by S. Smith)

These properties, including the dynamic shear modulus (G*) and the phase angle (δ), were found over a range of temperatures at a strain rate of 12% and are displayed in Table 3. According to Table 1 of ASTM D6373, the rheological properties of PG 64-22 binders should be tested at 147.2°F using a DSR. Minimum values of the parameter G*/sin(δ) are specified for all original and rolling thin film oven (RTFO) aged binders. For the original PG 64-22 binder, the G*/sin(δ) value should be above 1.0 kPa, and for the RTFO aged binder, this value should be above 2.2 kPa. The procedure for obtaining the asphalt emulsion residue simulates RTFO aging, so the G*/sin(δ) value at 147.2°F for this emulsion residue should be greater than 2.2 kPa. Although the emulsion residue was not tested at exactly 147.2°F, the G*/sin(δ) value at 145°F is 2.18 kPa. Therefore, the value of this parameter falls slightly below the recommended minimum for the emulsion residue.

TABLE 3. Asphalt Emulsion Residue Properties

Temperature (^{o}F)	Binder G* (Pa)	Phase Angle (^{o})
85	312937	71
100	83387	75
115	22704	79
130	6741	82
145	2176	85
160	787	87

After identifying the OMC and the SE, the OEC was selected using the Indirect Tensile Strength (ITS) test (ASTM D4867), which evaluates moisture susceptibility of asphalt mixtures. Each mixture was tested at four different emulsion contents, and the content that produced the maximum conditioned and unconditioned strengths was selected as the OEC. All emulsion-stabilized samples were fabricated using the Superpave Gyratory Compactor (SGC), compacting samples to 30 gyrations as specified by the mix design. Following compaction, the bulk specific gravity was determined for each sample according to ASTM D6752. The theoretical maximum specific gravity (ASTM D2041) was also found for each mixture and was then used to determine the percentage of air voids (ASTM D3203). These volumetric properties were also used to further characterize each mixture and as inputs into the MEPDG. Table 4 summarizes some of these material properties of each of the three FDR mixtures.

TABLE 4. FDR Mixture Material Properties

Property	Test Method	Sharp's Quarry Mix	Highway 5	Highway 36
Unit Weight (pcf)	ASTM D6752	132	131	134
Air Voids (%)	ASTM D3203	12	13	11
Water Added (%)	NCDOT	2.5	3.7	3.2
OEC (%)		4.8	6.0	6.0
Conditioned ITS (psi)	ASTM D4867	41.4	9.7	13.9
Unconditioned ITS (psi)		66.5	67.1	59.7

Laboratory Tests

The MEPDG uses different material properties to characterize asphalt concrete than it does for unbound granular materials. For asphalt concrete (AC), the structural characterization is done primarily with the dynamic modulus (E*). Asphalt binder properties including the complex shear modulus (G*) and the phase angle (δ) are required for rutting predictions. Additionally, low temperature cracking is predicted using the indirect tensile strength at 14°F and the creep compliance at a series of loading times and temperatures. Unbound granular materials (UGM), however, are characterized primarily by the resilient modulus (M_r). In order to create MEPDG models using the highest, most site-specific level of inputs, laboratory tests were completed to determine all of these material properties. Three replicates were used for every test in order to ensure representative and statistically reliable values were collected. Table 5 summarizes the tests completed in this research, as well as the layer type that required this input and the specification followed.

TABLE 5. Material Characterization Testing Summary

	FDR as AC	
Asphalt Mixture	Dynamic Modulus	AASHTO TP-62
	Dynamic Modulus (IDT)	Kim et al., 2004
	Creep Compliance IDT Strength	AASHTO T322
Asphalt Binder	Complex Shear Modulus Phase Angle	AASHTO T315
	FDR as UGM	
Resilient Modulus		AASHTO T307

Sample Fabrication

One of the difficulties with completing asphalt concrete laboratory tests on FDR materials is fabricating samples and cutting, coring, or compacting them to the required dimensions. Because these mixtures are not as stable as asphalt concrete and have larger aggregate, even after curing, they are often damaged or destroyed in the cutting process. Therefore, FDR samples were frozen prior to cutting to make the material stiffer and help ensure a smoother cut surface. According to research completed by Robinette and Williams, there is no statistical difference between dynamic modulus values for specimens compacted to the testing dimensions and specimen cut/cored to these dimensions (2006). Therefore, rather than coring these mixtures, samples were compacted in a 4-inch diameter SGC mold for both the uniaxial dynamic modulus test and the resilient modulus test. Figure 3 shows examples of samples of each FDR mixture used for resilient modulus testing and testing in the indirect tension configuration after being compacted and cut to the designated sample size.

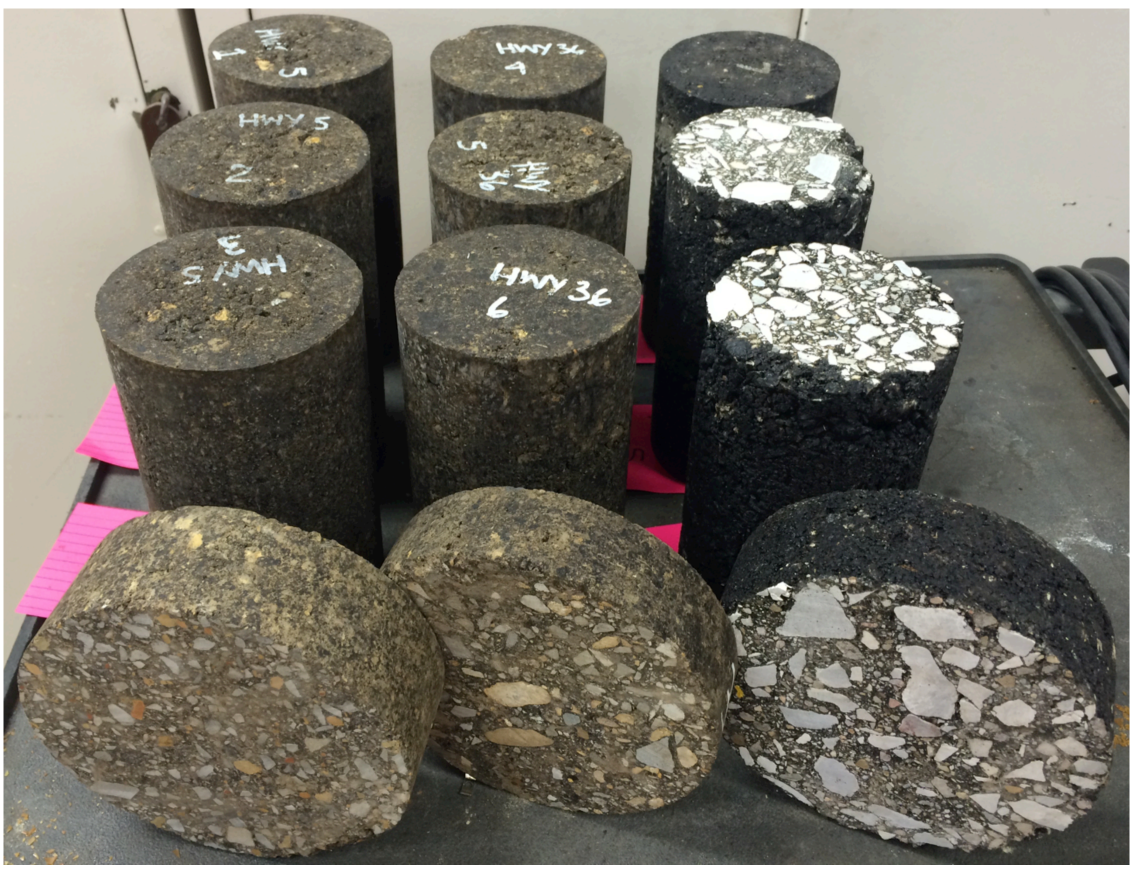


FIGURE 3. Samples Fabricated for Laboratory Testing (Photo taken by S. Smith)

Some uncertainty arises with compacting samples to a particular height, however, because the NCDOT mix design for FDR as well as other mix designs reviewed recommend a fixed 30 gyrations rather than a target percentage of air voids (NCDOT; Thomas & May, 2007). This is another aspect of the characterization of FDR that gives rise to the question of whether procedures typical for soils should be followed or those typical of asphalt concrete. When compacting soils, or unbound granular materials, proctor compaction is used, which prescribes a fixed number of blows of the hammer over a specific number of layers. Whereas, in the compaction of asphalt concrete, a target percentage of air voids is set and the number of gyrations is changed to reach that density. When compacting FDR samples of different heights for this research, the same 30 gyrations were used for all samples in order to consistently follow the mix design recommendations. Although, these taller samples had a higher percentage of air voids than the shorter samples, as would be expected. Further research should explore the influence of air voids in FDR mixtures and what the target of compaction should be, whether that be a fix number of gyrations or a target percentage of air voids.

Another challenge experienced in this research regarding sample fabrication was the limited amount of field material available from Highway 5 and Highway 36. Because these materials were sampled from sections of these highways, it was necessary to be conservative with the materials available. One way in which this was accomplished was by performing the dynamic modulus test on samples in the indirect tension (IDT) configuration as developed by Kim *et al*., rather than the typical uniaxial configuration. This research presented a modified procedure for completing dynamic modulus using the IDT method, and when compared to the original uniaxial method, the dynamic modulus master curves were found to be in good agreement (Kim *et al.*, 2004). Using this configuration allowed for the same samples to be used to find creep compliance, dynamic modulus, and indirect tensile strength. This method of using a testing suite for limited field materials was validated by research completed by Wagoner *et al.* (2006).

Asphalt Concrete Characterization Tests

Three different laboratory tests were completed on each of the FDR mixtures to obtain the material properties necessary for asphalt concrete characterization in the MEPDG. These tests included the dynamic modulus, the IDT creep compliance, and the IDT strength. As mentioned previously, for the sake of material conservation, the dynamic modulus test was performed in the IDT configuration as well. Therefore, all three tests could be performed on the same three replicate samples, as both the dynamic modulus and creep compliance are non-destructive tests. The dynamic modulus test was performed according to the procedure outlined by AASHTO TP-62 with the modifications presented by Kim *et al.* (2004). This involved testing each sample at six different frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz) and five different temperatures (14, 40, 70, 100, and 130°F), beginning with the highest frequency and lowest temperature. A master curve was then generated for each mixture, with 70°F as the reference temperature, plotting dynamic modulus against reduced frequency. Because there was not a restriction on material for the Sharp's quarry mix, dynamic modulus was performed in both the uniaxial and IDT configurations in order to confirm the findings from Kim *et al.*, for this type of material. Creep compliance and indirect tensile strength are used for low-temperature performance predictions by the MEPDG. The creep compliance was performed at -4, 14 and 32°F, while the indirect tensile strength was only measured at 14°F, as prescribed by AASHTO T322.

Unbound Granular Material Characterization Tests

The primary characterization for unbound materials is done with the resilient modulus. This test was completed according to AASHTO T307 for base materials. The confining pressure was applied using the house air pressure at the University of Arkansas Engineering Research Center and the air pressure board shown in Figure 4(a). As previously discussed, material was limited for the Arkansas highway mixtures; so 4-inch diameter samples were tested, rather than the recommended 6-inch diameter samples. This sample size did not adhere to the minimum diameter of five times the maximum particle size required by AASHTO T307, which would have required a minimum sample diameter of 5-inches. However, there was not enough material available from Highway 5 and Highway 36 to fabricate 6-inch diameter by 12-inch tall samples to adhere to these requirements. Additionally, performing this test in a smaller triaxial cell did not require the removal of the environmental chamber from the MTS loading frame used to perform these tests; whereas, using the larger triaxial cell would have been impossible with the environmental still in place. Figure 4(b) displays this testing configuration with the triaxial cell placed inside the environmental chamber.

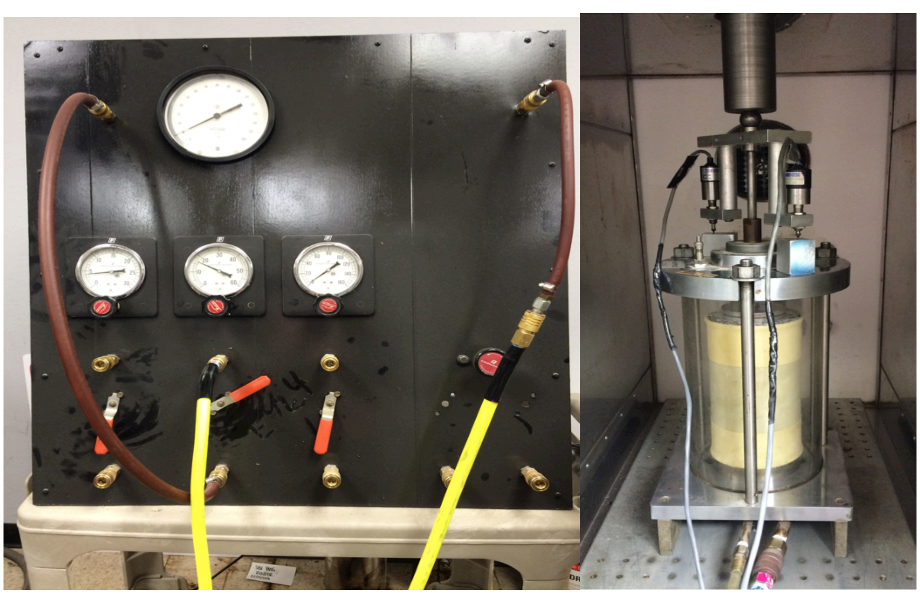


FIGURE 4. Resilient Modulus Testing Configuration (Photo taken by S. Smith)

MEPDG Models

In order to observe the effects of considering FDR as asphalt concrete versus considering it as an unbound granular material on the performance of the pavement structure, two different MEPDG models were created for each of the three FDR mixtures. The material properties that were determined from laboratory tests were used in conjunction with some properties that were left as default values, Arkansas climate data, and traffic data from each of the Arkansas highways selected. The same structural design, with the exception of the FDR layer itself, was used for each of these models. The surface layer was assumed to be a 1-inch asphalt concrete layer, characterized by all of the default properties. A 1-inch layer was selected because this is the minimum layer thickness allowed by the MEPDG software, and will allow for the FDR layer to have the largest influence on the simulations. The subgrade material was selected as the default A-2-6 soil given by the software because this was the type of subgrade soil collected for both Highway 5 and Highway 36. And as mentioned previously, an 8-inch FDR layer was placed in between this surface and subgrade. Figure 5 diagrams these structures as entered into the MEPDG, for both FDR as asphalt concrete and FDR as an unbound granular material.

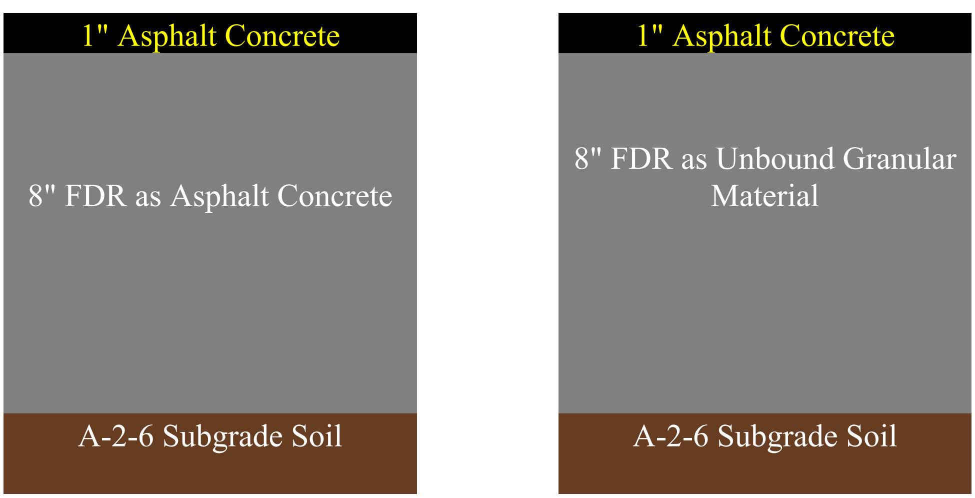


FIGURE 5. Diagram of FDR Structural Design

Some material properties were left as the default values given by the software due to inability or impracticality of completing the laboratory tests necessary to determine these values. These properties left as default values include the asphalt concrete thermal properties as well as the coefficient of lateral earth pressure and the saturated hydraulic for the unbound granular materials. Poisson's ratio was also left as the default value of 0.35 due to difficulty in measuring this value from the tests performed.

Traffic data was obtained for the sampled sections of each highway from the Arkansas State Highway and Transportation Department (AHTD). The data collected was based on necessary inputs for the MEPDG traffic predictions as well as availability of the information to AHTD. Information regarding the number and types of trucks traveling along these sections of highway was of particular interest, including the overall percent of trucks, the two-way annual average daily truck traffic (AADTT), and the vehicle class distribution. Table 5 summarizes this data for each of the two highways.

TABLE 5. Arkansas Highway 5 and Highway 36 Traffic data

Traffic Data	**Highway 5**	**Highway 36**
Two-Way AADTT	460	24
Number of Lanes	2	2
% Trucks in Design Lane	50	50
% Trucks in Design Direction	80	80
Growth Rate (%)	0.0	1.6
Overall % Trucks	10	5
Vehicle Class Distribution (% of Trucks)		
Class 4	5.26	26.09
Class 5	11.58	32.61
Class 6	16.84	6.52
Class 7	4.21	2.17
Class 8	11.58	8.70
Class 9	47.37	23.91
Class 10	3.16	0.00
Class 11	0.00	0.00
Class 12	0.00	0.00
Class 13	0.00	0.00
Class 14	0.00	0.00

An educational version of AASHTO's Pavement ME software was used, so the climate files available for performance predictions were limited. Therefore, Fayetteville, Arkansas was selected in order to closely simulate the climate in which the FDR sections would be constructed in Arkansas.

RESULTS AND DISCUSSION

The objective of this research was to evaluate the effectiveness of the existing MEPDG software for the design of asphalt stabilized FDR by comparing the effects of considering this type of FDR as an asphalt concrete material versus considering it as an unbound granular material. This was completed by obtaining all material properties necessary for both types of characterization and then creating the MEPDG models for both layer types and each FDR mixture.

Material Characterization

Asphalt Concrete Characterization

The characterization of FDR as an asphalt concrete material included the dynamic modulus, creep compliance, IDT strength, and rheological properties of the asphalt emulsion residue. The dynamic modulus test was performed on all three mixtures in the IDT configuration and in the traditional uniaxial configuration for the Sharp's Quarry Mix. The master curves created for each of these tests are displayed in figure 6. Because asphalt concrete is a viscoelastic material, the temperature of the material and the time or frequency of loading affects its stiffness. The dynamic modulus evaluates the stiffness at a number of different temperatures and frequencies, which can then be used to generate the master curve that predicts a mixture's stiffness in any temperature or under any frequency. From this graph, it is evident that Sharp's Quarry Mix completed in the uniaxial configuration yielded the highest E* values at higher frequencies. There is a large gap in the stiffnesses of this mixture when performed in the two different configurations. The exact reason for this could not be determined, however, it may be a function of the geometry and FDR not performing as well in a tensile configuration as a typical asphalt concrete mix. Another reason for this difference may be that FDR has a larger nominal maximum aggregate size (NMAS), therefore, the smaller IDT samples may allow for more influence from the specific aggregate sizes in each cut. It is also interesting to note that all of the master curves seem to converge near 0.01 Hz and all nearly reach 0 as the reduced frequency approaches 0. This result was not surprising because during testing, all three mixtures became very difficult to handle at the warmest temperatures. Metal gauge points, which are glued onto the samples, fell off very easily or were pulled off of the samples with the extensometers at the warmest temperatures, which showed that the glue was stronger than the cohesion of the sample itself. While all three mixes became noticeably softer at 130°F, the Sharp's Quarry Mix samples were the most difficult to test at this temperature. This was interesting given that this mixture was also the stiffest at the colder temperatures.

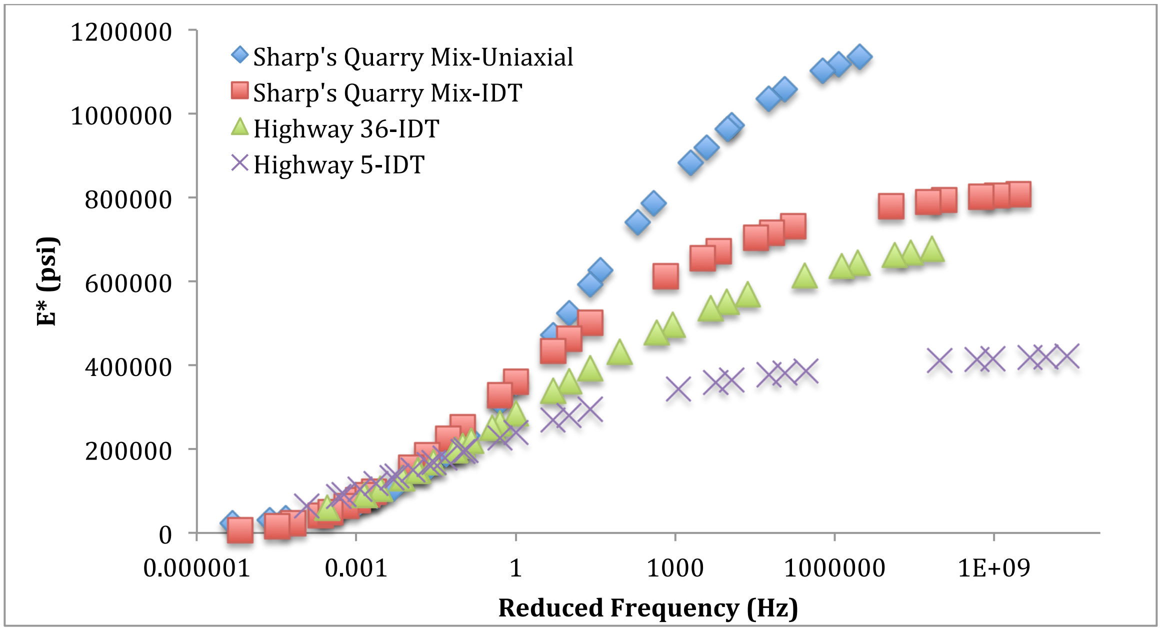
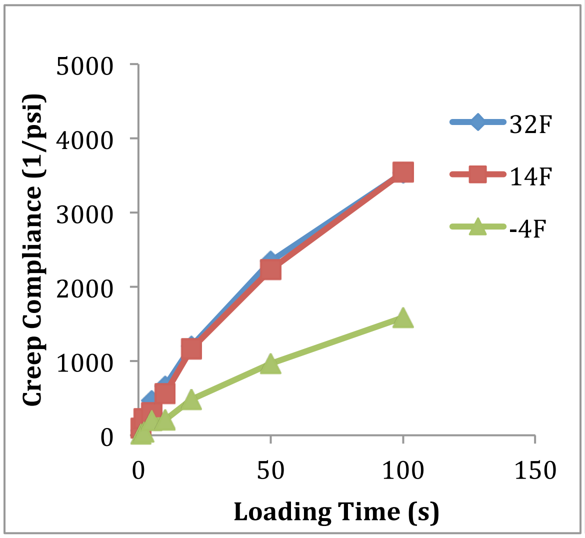
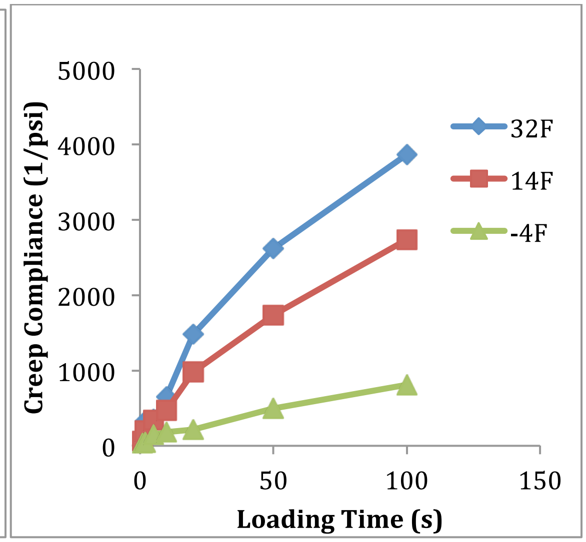


FIGURE 6. Dynamic Modulus Master Curves

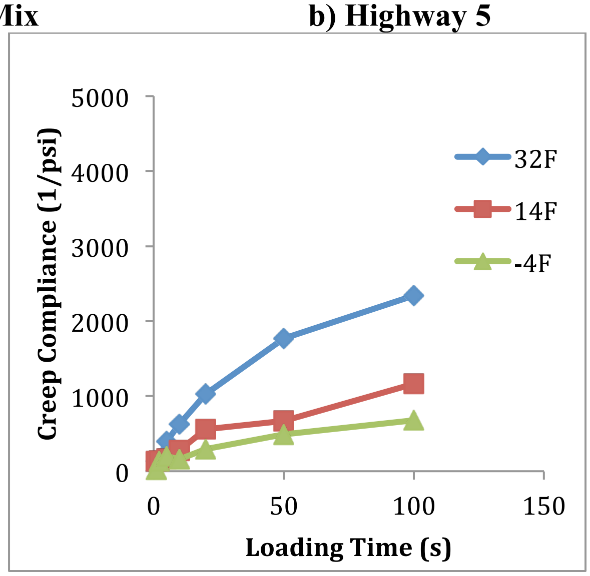
Low temperature characterization for the FDR mixtures was done using the creep compliance and the IDT strength at 14°F. In general, the higher the creep compliance and IDT strength, the greater resistance the mix has to thermal cracking (Apeagyei and Diefenderfer, 2011). Figure 7 shows the creep compliance values at six different loading times (2, 5, 10, 20, 50, and 100 seconds) as required by the MEPDG for inputs. The Sharp's Quarry Mix had the highest creep compliance values for all temperatures with the exception of a few loading times at 32°F, as shown in Figure 7(a). Highway 5, displayed in Figure 7(b), had similar creep compliance values to the Sharp's Quarry Mix for 32°F; however, at 14°F and -4°F, it drops lower than those for the quarry mix. Highway 36 had the lowest creep compliance values overall, which are displayed in Figure 7(c), but the values at -4°F were very similar to those of Highway 5. During creep compliance testing, the question arose as to whether the viscoelastic limits given in AASHTO T322 could be applied to FDR given that those are based upon asphalt concrete materials. No cracks were found in these samples during or after testing and strains were kept in the lower end of the allowable range. However, further research should be completed to investigate whether this range is appropriate for FDR materials as well as asphalt concrete materials.



a) Sharp's Quarry Mix



b) Highway 5



c) Highway 36

FIGURE 7. Creep Compliance by FDR Mixture: a) Sharp's Quarry Mix; b) Highway; c) Highway 36

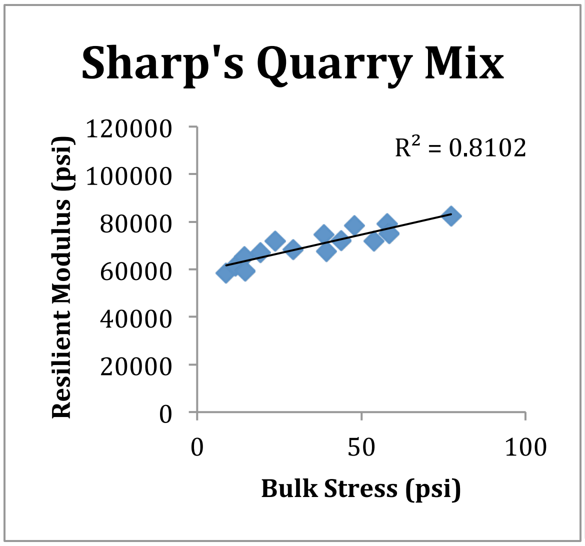
The IDT strength of each mixture at 14°F did not follow the same trend that the creep compliance did. Although, the ranking of IDT strengths for the three mixtures is the same as that of the stiffness as predicted by the dynamic modulus. Sharp's Quarry Mix had the highest results for all three tests; however, for dynamic modulus and IDT strength, Highway 36 had higher stiffness and strength values than Highway 5. Whereas, for creep compliance, Highway 5 had higher values than Highway 36. Table 6 lists the strength values determined for each mixture.

TABLE 6. IDT Strength at 14°F

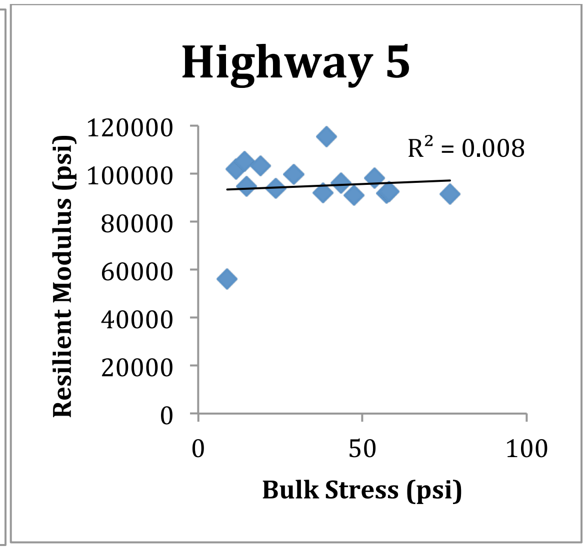
Sharp's Quarry Mix	201.2 psi
Highway 5	125.5 psi
Highway 36	163.6 psi

Unbound Granular Material Characterization

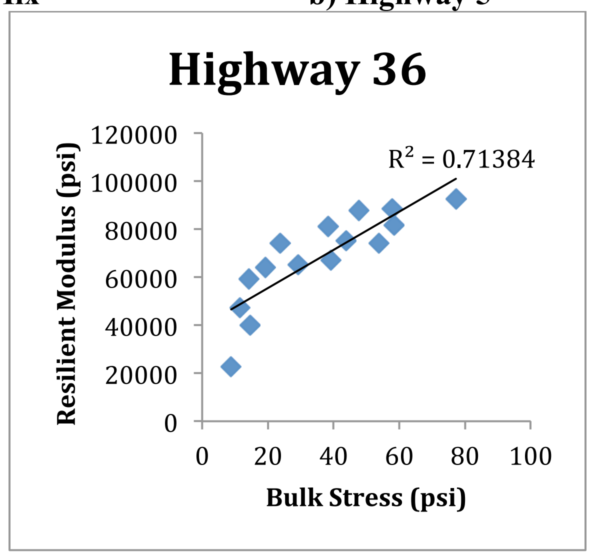
The resilient modulus serves as the primary strength and stiffness characterization for the unbound granular materials. This property is obtained on base or subbase soils in a fifteen different stress states to allow for the prediction of the stiffness of a soil material in any stress state. Typically, unbound granular materials are assumed to be stress-dependent, or stress hardening, materials. This means that as the stress state increases, the stiffness or modulus increases as well (NCHRP, 2004). Figure 8 shows the relationship between bulk stress, which is calculated by summing the confining stresses and the cyclic axial stress applied in each loading sequence of the resilient modulus test, and the resilient modulus. As seen in figures 8(a) and 8(b), the resilient modulus values for the Sharp's Quarry Mix and Highway 5, respectively, were not as significantly affected by the increase in stress state as a typical unbound granular material.



a) Sharp's Quarry Mix



b) Highway 5



c) Highway 36

FIGURE 8. Resilient Modulus versus Bulk Stress by FDR Mixture: a) Sharp's Quarry Mix; b) Highway; c) Highway 36

According to Rao *et al.*, increasing the bulk stress yields a significant change in measured resilient modulus of approximately 55% from the initial stress state to the final stress state for coarse-grained soils, or unbound granular materials (2012). For these two mixtures, there was an increase of about 25% from initial to final stress state for Sharp's Quarry Mix and about 50% for Highway 5. There does not seem to be a relationship between modulus and stress state for Highway 5, however, and with the exception of the first stress state, the modulus values only change by about 20% through the various stress states. In Figure 8(c), Highway 36 shows a stronger, positive correlation between modulus and stress state, similar to Sharp's Quarry Mix. Although, the moduli of this mixture are much more strongly influenced by bulk stress than the other two FDR mixtures, as there is an increase in resilient modulus of about 76% from the initial stress state to the final stress state, which is much more typical of unbound granular materials.

Initially, the MEPDG used a generalized constitutive model to predict the stiffness in any stress state after fitting it to the laboratory calculated resilient modulus values using a nonlinear regression analysis. Three regression constants were then used as the level 1 input into the MEPDG. However, the Pavement ME software, as was used in this research, does not allow for this level of input. Because a level 1 analysis was not possible, an average resilient modulus value was calculated for each mixture to be used as a representative annual value for a level 2 analysis. These representative annual values are summarized in Table 7. It's interesting to note that the relative stiffness when comparing the three mixtures does not match the trend seen in dynamic modulus values for these mixtures. In the case of resilient modulus, Highway 5 had the highest value, whereas, Sharp's Quarry Mix had the highest dynamic modulus values, followed by Highway 36 and then Highway 5.

TABLE 7. Average Annual Representative Resilient Modulus Values

Sharp's Quarry Mix	70176
Highway 5	94876
Highway 36	68067

The modulus values of two of the FDR mixtures did not vary with stress state as would typically occur for unbound granular materials; although, the modulus of Highway 36 behaved much more like an unbound granular material. However, because all mixtures are stabilized with asphalt emulsion, they are more resistant to moisture than an unbound material would be. Unfortunately, without the level 1 analysis as an option, the MEPDG models for unbound granular materials automatically vary the resilient modulus based upon stress state and moisture, as determined by the traffic and climate data. Therefore, both Sharp's Quarry Mix and Highway 5 were forced to behave as unbound granular materials, which the resilient modulus results proved to be incorrect. This may then yield inaccurate performance predictions by the MEPDG because the modulus of the material is being incorrectly modeled. According to NCHRP 1-47, asphalt concrete only rutting, total rutting, and top-down fatigue cracking are all sensitive to the resilient modulus. Bottom-up fatigue cracking is very sensitive to the resilient modulus, and thermal cracking is not sensitive to the resilient modulus (Schwartz *et al.*, 2011). So all but one of these distress predictions is significantly affected by the modulus, making inaccurate modeling of the modulus for Sharp's Quarry Mix and Highway 5 a significant consideration when evaluating these results.

Comparing Material Types

As previously discussed, FDR is a unique material because during the recycling process, a composite material is created that combines RAP, granular base material, and some of the subgrade soil. Therefore, it is not exactly an asphalt concrete material, nor is it a completely unbound granular material. So when considering the material characterization of this new type of material, it is important to understand what most significantly affects the performance of each of these types of materials and then determine where FDR may fit between the two. Asphalt concrete is a viscoelastic material; therefore, temperature and the time or frequency at which a load is applied most significantly affect the stiffness and strength. Soils or unbound granular materials are non-linear materials, and the strength or stiffness of these materials is most significantly influenced by stress state and moisture (NCHRP, 2004). The dynamic modulus and resilient modulus evaluate the stiffness of asphalt concrete and unbound granular materials, respectively, as it is affected by these most significantly influential factors. Distress predictions by the MEPDG are equally sensitive to the two types of moduli in a pavement structure, according to NCHRP 1-47 (Schwartz *et al.*, 2011). In the case of FDR then, to select which modulus value may be of more interest. Both the dynamic modulus and the resilient modulus are a measure of stress divided by recoverable strain. In order to compare these modulus values to evaluate whether the moduli of FDR is more significantly influenced by temperature or stress state, the correlation between dynamic modulus at10 Hz and temperature were compared to the correlation of the resilient modulus with bulk stress. While the modulus at all five temperatures was considered, only the dynamic modulus values at 10 Hz were used because this frequency most closely simulates the loading frequency of the resilient modulus test, and this helps isolate the influences of temperature and stress state on modulus. These correlation values are summarized in Table 8. Based upon these values, it is evident that there is a stronger correlation between temperature and modulus than for bulk stress and modulus. This gives evidence to the belief that FDR mixtures may be most accurately characterized as a less aged asphalt concrete (You *et al.*, 2012).

TABLE 8. Correlation Between Moduli and Temperature vs. Moduli and Bulk Stress

	Sharp's Quarry Mix	Highway 5	Highway 36
Temperature	-0.988	-0.984	-0.965
Bulk Stress	0.900	0.089	0.845

MEPDG Results

Once all of the necessary material properties were obtained, the MEPDG models were created using the structural design, climate files, and traffic data mentioned in the previous section. Because the Sharp's Quarry Mix had no traffic of its own, this material was modeled under both Highway 5 and Highway 36 traffic. This also allows for the evaluation of the influence of traffic on one of the FDR mixtures. Because all of these models were created as a new flexible pavement within the MEPDG, there were six different distresses as the performance criteria: International Roughness Index (IRI), Total Rutting, Asphalt Concrete Rutting, Bottom-Up Fatigue Cracking, Top-Down Fatigue Cracking, and Thermal Cracking. Table 9 summarizes all of these distress predictions for each of the three mixtures and both layer types.

TABLE 9. Summary of MEPDG Distress Predictions

FDR as AC				
Distress	SQM (5)	SQM (36)	HWY 5	HWY 36
IRI (in/mi)	138.3	125.01	148.36	125.69
Total Rutting (in)	0.4	0.2	0.52	0.22
AC Rutting (in)	0.11	0.03	0.2	0.04
Fatigue Cracks (BU) (%)	21.81	1.37	32.79	1.31
Fatigue Cracks (TD) (ft/mi)	205.8	170.49	730.34	174.7
Thermal Cracks (ft/mi)	18.19	18.19	18.19	18.19
FDR as UGM				
Distress	SQM (5)	SQM (36)	HWY 5	HWY 36
IRI (in/mi)	143.99	132.94	164.12	163.85
Total Rutting (in)	0.65	0.39	1.15	1.11
AC Rutting (in)	0.03	0.01	0.49	0.13
Fatigue Cracks (BU) (%)	0.96	0.95	0.95	0.95
Fatigue Cracks (TD) (ft/mi)	644.84	199.03	1173.5	363.38
Thermal Cracks (ft/mi)	18.19	18.19	18.19	18.19

In order to compare the effects of considering these three FDR mixtures as an AC versus as UGM, the final distress predictions from each MEPDG model were plotted against one another as shown in Figure 9 through Figure 11. It is important to note that because the materials in an FDR mixture will vary significantly depending on the in-situ materials and the stabilization technique selected, these results may not be the same for all FDR mixtures. Rather, it is interesting to observe the general trends and how material characterization affects the performance predictions by the MEPDG. Overall, the distress predictions were higher when FDR was considered to be an unbound granular material, with the exception of bottom-up fatigue cracking and asphalt concrete only rutting for the Sharp's Quarry Mix.

The IRI predictions were the most similar for all mixes and layer types. Figure 9 displays this trend with all four data points located close to the line of equality. When considered as an UGM, the two highway mixtures and the quarry mixture with both sets of traffic data had similar IRI predictions. However, when FDR was considered as an AC layer, the IRI predictions were more similar for the models with the same traffic data, rather than the same materials.

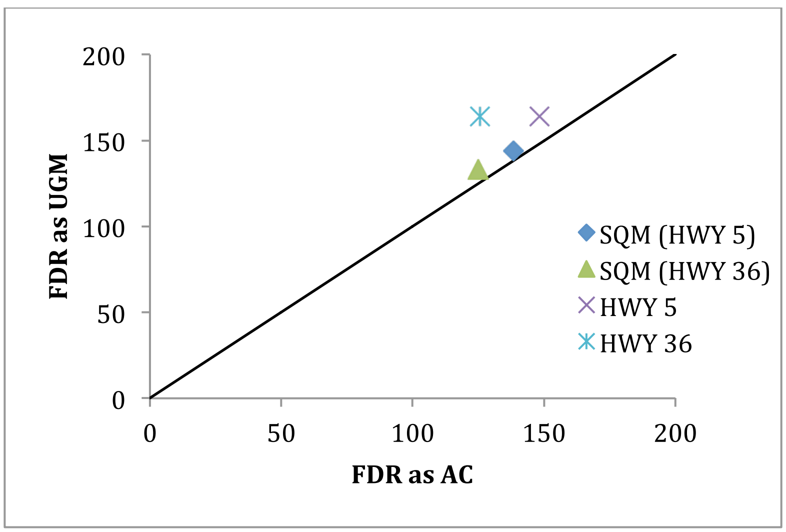
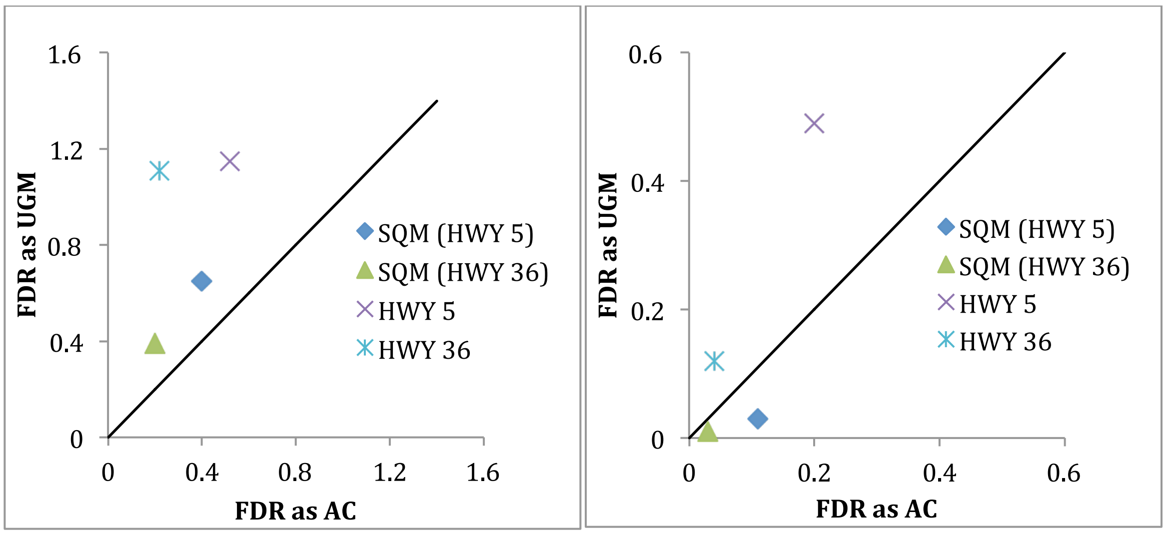


FIGURE 9. IRI Predictions for FDR as AC vs. FDR as UGM (in/mi)

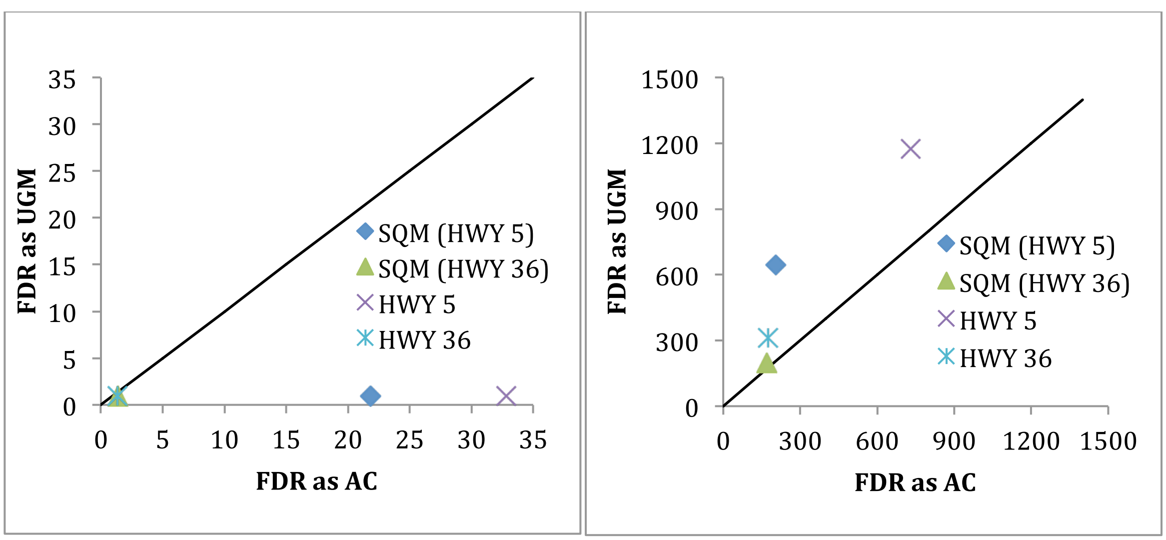
Figure 10 (a) and 10 (b) compare the total rutting and asphalt concrete only rutting predictions, respectively. By considering both the total rutting and the AC rutting, the amount of rutting that occurs in the FDR layer and the subgrade can be isolated for the MEPDG models that consider FDR as an UGM. For both AC rutting and total rutting, the Sharp's Quarry mixture predictions were close to the line of equality. It is interesting to note that the Sharp's Quarry mixture AC only rutting predictions were higher for FDR as AC than they were for FDR as UGM, which is one of the only distresses for which this occurs. Additionally, the FDR as UGM models failed in total rutting for the two highway mixtures because the total rutting predictions were higher than the limit of 0.75-inches. This prediction may not be accurate, however, because considering FDR as an UGM does not account for the added stability of the asphalt emulsion in the mix.



a) Total Rutting (in) **b) AC Rutting (in)**

FIGURE 10. Rutting Predictions for FDR as AC vs. FDR as UGM: a) Total Rutting (in); b) AC Rutting (in)

The two types of fatigue cracking evaluated by the MEPDG are bottom-up and top-down fatigue cracking. Both occur due to a weakening of the asphalt concrete layer as it is subjected to repeated loads over time. This creates tensile strains either in the top of the asphalt concrete layer, for top-down cracking, or in the bottom of the asphalt concrete layer, for bottom-up fatigue cracking, that lead to cracks in the material. Bottom-up fatigue cracking predictions were the only ones that were consistently higher for all three mixtures when FDR was considered as AC. This result was not expected as considering FDR as AC should yield a structure with more tensile strength than considering FDR as UGM. In each of these models, the MEPDG is evaluating a structure with 9-inches of asphalt concrete for FDR as AC against a structure with only 1-inch of asphalt concrete for FDR as UGM. Therefore, the expected result would be that there would be far more bottom-up fatigue cracking in the pavement structure with only 1-inch of asphalt concrete. One reason for the higher bottom-up fatigue cracking predictions when FDR was considered as AC is that the low tensile strength of the FDR mixtures allowed for more cracks to start occurring at the bottom of this 8-inch FDR layer, which could then propagate up to the surface course. Because fatigue cracking occurs due to repeated loads over time, it is consistent to see such a significant difference in the distress predictions for the models with the two different traffic volumes. Both Sharp's Quarry Mix with Highway 5 traffic and the Highway 5 models considering FDR as AC had much higher percentages of bottom-up fatigue cracking than the two models that used the lower, Highway 36 traffic data. Top-down fatigue cracking had very similar values for FDR as AC except the Highway 5 mixture. In the case of top-down cracking, traffic volume seemed to have a stronger influence on the distress predictions for FDR as UGM.



a) Bottom Up Fatigue Cracking (%) **b) Top Down Fatigue Cracking (ft/mi)**

FIGURE 10. Fatigue Cracking Predictions for FDR as AC vs. FDR as UGM: a) Bottom Up Fatigue Cracking (%); b) Top Down Fatigue Cracking (ft/mi)

As discussed previously, all MEPDG models for this research were run using the climate data for Fayetteville, Arkansas. Thermal cracking predictions were the same for all three mixtures, when considered as both AC and UGM, which was a value of 18.19 feet per mile. Schwartz *et al.* found that thermal cracking predictions were not sensitive to traffic volume, dynamic modulus, or resilient modulus. However, these predictions were sensitive to binder stiffness, creep compliance, and tensile strength (Schwartz *et al.*, 2011). Both creep compliance and tensile strength varied significantly between mixtures, so it is interesting that thermal cracking predictions remained the same for all. For further research, the effects of harsher climates on thermal cracking should be evaluated for asphalt emulsion FDR mixtures.

CONCLUSIONS

While FDR has many potential benefits, there are some limitations due to lack of understanding of material characterization and the structural design procedure. During the FDR process, a composite material is created by combining RAP, granular base material, and some of the subgrade soil. Therefore, it is absolutely essential that material characterization techniques, and consequently, structural design procedures, are adapted and modified to allow for the consideration of the unique capabilities this recycled, stabilized base course can provide within a pavement structure. In this research, the structural design of asphalt emulsion FDR was evaluated by considering this material as an asphalt concrete layer and as an unbound granular material using the MEPDG software. These are some of the major conclusions:

- The modulus of asphalt emulsion FDR is more strongly correlated to temperature than stress state; therefore, the dynamic modulus test may be of more interest to run on this type of material than the resilient modulus test.
- All distress predictions were higher for FDR as UGM except for AC rutting in the Sharp's Quarry Mix and bottom-up fatigue cracking.
- Thermal cracking was the same for every model, regardless of material or layer type; therefore, this distress is mostly affected by climate.
- Traffic volume seemed to influence all distresses more for FDR as AC than the mixture properties, with the exception of thermal cracking and top-down fatigue cracking.
- Despite having the highest resilient modulus, all distress predictions for Highway 5 as UGM were the largest. This is also interesting given the sensitivity of the MEPDG performance predictions to resilient modulus.
- Overall, it is evident that considering asphalt emulsion FDR as AC versus considering asphalt emulsion FDR as UGM significantly affects distress predictions by the MEPDG for all distresses except thermal cracking.

FUTURE RESEARCH

Based upon the findings of this research, future research should include the following:

- Determine if the IDT configuration can be used for dynamic modulus testing on FDR materials given the significant difference seen in these values for the Sharp's Quarry Mix.
- Confirm that the viscoelastic range of asphalt concrete is the same for FDR or determine what these limits actually are for FDR.

- Explore whether a fixed number of gyrations should be used for sample fabrication or if there should be a target percentage of air voids.
- Explore the effects of the different layer types and methods of material characterization on other FDR technologies, including asphalt foam, cement, and combinations of these. Because a cement-stabilized base is already an option for material type within the MEPDG, it would be interesting to see how the use of cement in FDR affects the results found in this research.

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